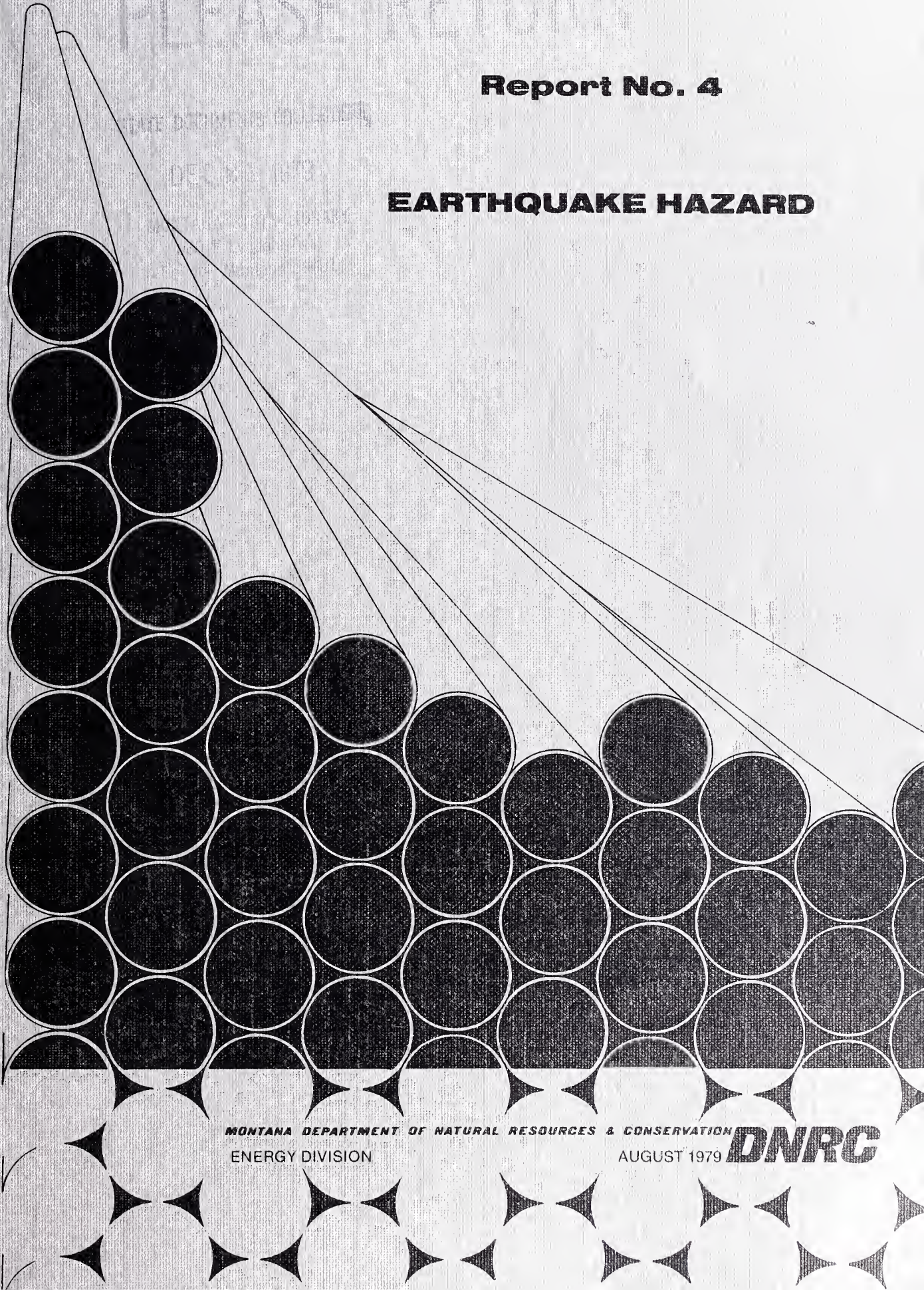


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NORTHERN TIER

Report No. 4

EARTHQUAKE HAZARD



MONTANA DEPARTMENT OF NATURAL RESOURCES & CONSERVATION **DNRC**
ENERGY DIVISION

AUGUST 1979

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Northern Tier Report No. 4

**EARTHQUAKE HAZARD TO THE
PROPOSED NORTHERN TIER PIPELINE IN MONTANA**

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August 1979



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ABBREVIATIONS

a	acceleration
cm	centimeter
DNRC	Department of Natural Resources and Conservation
EIS	environmental impact statement
g	gravitational acceleration = 980 cm/s^2
I	intensity
in	inch
km	kilometer
M	magnitude
m	meter
mi	mile
NOAA	National Oceanic and Atmospheric Administration
NTPC	Northern Tier Pipeline Company
s	second
USDC	United States Department of Commerce
USDI	United States Department of the Interior
USGS	United States Geological Survey

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This report was prepared by Anthony Qamar, University of Montana, Geology Department and Ray Breuninger, DNRC Energy Division. Shari Meats edited the report. Steve Alsup, a consultant on seismic hazards with NTPC, Robert Curry, University of Montana, Geology Department, and Mike Burnside, geologist with the USDA Forest Service, Lolo National Forest provided technical reviews of the information. Tom Wing, a private engineering consultant, and Jack Crank, of Gulf Interstate Engineering Company, provided information on crude-oil pipeline system design and construction.

Others from DNRC who assisted in the report's preparation include: Lee Shelton, who made metric conversions and compiled the list of abbreviations, glossary, and literature citations; Pam Goddard and Denise Thompson, who typed the manuscript; June Virag, who prepared the illustrations; and D.C.Howard, who designed the cover of the report. Special thanks go to Dave Lambert for his editorial guidance and to Gary Wolf and Kathy Hanson for their assistance in preparing the report for publication.

CHAPTER ONE

INTRODUCTION

This report's analysis of earthquake hazard supplements the state's draft environmental impact statement (draft EIS) on the proposed Northern Tier Pipeline System (NTPS) in Montana. The Northern Tier Pipeline Company (NTPC) has proposed a 102-cm to 107-cm (40-in to 42-in) diameter underground pipeline system to transport crude oil from a tanker port at Port Angeles, Washington, to Clearbrook, Minnesota, traversing approximately 1,014 km (630 mi) of Montana en route.

Since Montana lies in an active earthquake zone, the Intermountain Seismic Belt, it is necessary to consider earthquake hazard along the proposed pipeline's route. Before such a discussion can begin, it is first necessary to understand how earthquakes are measured and what those measurements mean. Three basic measurements are used throughout this report to describe earthquakes: magnitude (M), intensity (I), and acceleration (a). Determination of the maximum magnitude, intensity, or acceleration likely to result from an earthquake at a site is essential in order to design the pipeline in such a way that it would not be damaged by an earthquake.

Magnitude is indicated by a number proportional to the amount of energy released by the earthquake. Usually it is calculated from the amplitude of seismic P waves or surface waves emitted by the fault, and is determined from measurements made from seismograms. Several magnitude scales, which roughly correspond to one another, are used to measure body and surface waves, and Richter (or local) magnitude. Each increase of one unit on the magnitude scale implies a ground motion ten times greater, or an energy release about thirty-three times greater.

Intensity is indicated by a number¹ (usually a Roman numeral) that measures the degree of shaking at a site based upon human reaction and structural damage. The intensity scale most commonly used in the U.S. is the Modified Mercalli; it ranges from I, a level usually not felt, to XII, indicating total damage. (A description of the Modified Mercalli ranges can be found in Appendix A.) Intensity generally decreases with distance from the epicenter.

Acceleration measures the rate of velocity change over time in cm/s^2 or g's. One g is equal to 980 cm/s^2 (32 ft/s^2), accelerations exceeding 1 g have been recorded in a few cases. Acceleration is determined from special seismograms called accelerograms, which are produced by instruments called

¹In this report, where modified Mercalli intensity measurements contain fractions, the fractions are shown in decimal form if: (a) a measurement appears in an equation, (b) intensities are contoured on a map, or (c) more than one significant figure is needed for accuracy.

accelerometers. The output of an accelerometer is directly proportional to ground acceleration. Acceleration generally decreases with distance from the epicenter.

Determination of present hazard begins with a review of data on past earthquakes, such as where they occurred and actual measurements of magnitude and intensity. Past data also can show how frequently earthquakes in specific regions are likely to recur. Such information can be used to specify that the pipeline be designed to withstand an earthquake of a certain magnitude and intensity. A review of the available data on past earthquakes in Montana and their recurrence rates is undertaken in the following section, entitled "Earthquakes in Montana." The data show that in western Montana, through which the pipeline's routing is proposed, an earthquake magnitude greater than 5 can be expected every 1.4 years, a magnitude greater than 6 every 10 years, and a magnitude greater than 7 every 77 years on the average.

After the discussion on past earthquakes in Montana, the risk of earthquake damage to pipelines is considered. It is known that earthquakes can produce ruptures in underground pipelines, but written information is scanty. For this report, information was gathered from documented reports of earthquake-caused damage to pipelines elsewhere in the United States and abroad. One conclusion that may be drawn from this section is that pipelines made with the advantage of modern design can generally withstand earthquakes of moderate magnitudes.

One of the most important considerations that arises from the same section is the necessity to investigate further the active and potentially active faults along the proposed and alternative routes suggested for the Northern Tier Pipeline. Among these are the Hope, Ninemile, Helmsville, Avon, and Helena Valley faults. (All are described in appendix B.) It would be very helpful to conduct geological and geophysical investigations to determine more about their seismic histories. NTPC has indicated that such studies will be conducted before centerline construction on all but the Hope Fault.

Finally, this report concludes by estimating the magnitude for which to design the Northern Tier Pipeline. Calculations show that a credible magnitude would be 6.75 to 7; the design could possibly include accommodation of an intensity of IX on the Modified Mercalli Scale.

This report is one in a series of six reports prepared to provide information supplementing that contained in the state's draft EIS. The series consists of the following reports:

- | | |
|----------|--|
| Report 1 | The Effects of Large-Diameter Underground Crude-Oil Pipelines on Soils and Vegetation, with Emphasis on the Proposed Northern Tier Pipeline in Montana |
| Report 2 | The Effects of Large-Diameter Underground Crude-Oil Pipelines on Wildlife, with Emphasis on the Proposed Northern Tier Pipeline in Montana |

- Report 3 The Effects of Large-Diameter Underground Crude-Oil Pipelines on Aquatic Life and Habitats, with Emphasis on the Proposed Northern Tier Pipeline in Montana
- Report 4 Earthquake Hazard to the Proposed Northern Tier Pipeline in Montana
- Report 5 The Effects of Large-Diameter Underground Crude-Oil Pipelines on Land Use, with Emphasis on the Proposed Northern Tier Pipeline in Montana
- Report 6 Social and Economic Impacts of the Proposed Northern Tier Pipeline in Montana

The reports are available on request from the Montana Department of Natural Resources and Conservation, Energy Division, 32 South Ewing, Helena, Montana, 59601, (406) 449-3780.

CHAPTER TWO

EARTHQUAKES IN MONTANA

MAPPING

Montana lies in a north-trending zone called the Intermountain Seismic Belt (Smith and Sbar 1974) in which earthquakes occur. This earthquake zone branches at Yellowstone National Park; one belt of activity trends westward into central Idaho and the other trends north and then northwest through Three Forks, Helena, and finally Flathead Lake. It is the latter branch, through western Montana, that the proposed Northern Tier Pipeline would cross. All of the historical earthquakes shown on map 5 of the draft EIS occurred in the Intermountain Seismic Belt.

At the earthquake laboratory of the University of Montana, data on earthquakes that occurred between September 1974 and September 1976 was collated and mapped. The map produced is on file at DNRC for public inspection. (The map includes also the 1978 Garnet Range earthquakes east of Greenough.) The activity pattern is consistent with historical data, but more detail is available. (Refer also to Montana Department of Military Affairs 1976 and Stickney 1978.)

Several other maps also were compiled at the earthquake laboratory; they too are on file at DNRC. They are:

- (1) A map showing maximum intensities on the Modified Mercalli Scale (greater than or equal to V) for earthquakes that occurred between 1925 and 1977
- (2) A map illustrating the cumulative energy release in Montana from past earthquakes
- (3) A map showing cumulative energy release for earthquakes that occurred between September 1974 and September 1976

These three maps give rough indications of the historically active earthquake zone in Montana.

One way to examine earthquakes is to consider the amount of strain energy released. Richter (1958) gives the relation:

$$\log E = 11.4 + 1.5 M$$

where: E = energy (in ergs)

M = surface wave magnitude of earthquake

The energy release by small events is a great deal less than the release by

large events. The equation implies that an increase of one magnitude unit results in an energy release thirty-three times greater. The cumulative energy release in Montana from historical earthquakes is dominated by the large events of westcentral and southwestern Montana. A similar energy release plot for recent earthquakes (from September 1974 to September 1977) shows that within this short time period, the energy release became spread out over a much broader area. However, it should be noted that a significantly longer time period would be needed to demonstrate a complete pattern. Exactly what the length of time should be is unknown.

The extensive network of detectors used to detect the small recent earthquakes may help to explain this change in energy pattern. However, most of the energy release from earthquakes in a region results from the larger events. The time period for the earthquakes used to produce the map enumerated under number 2 above was not long enough to obtain a good statistical sample of larger events. Hence, it may be that the pattern in the map shows a more representative long-term average energy release. However, the pattern is dominated mainly by the large events in Helena, Three Forks, and Hebgen. The time period for which historical earthquake data in Montana is available is not really sufficient to obtain an average energy release of events exceeding magnitude 6.

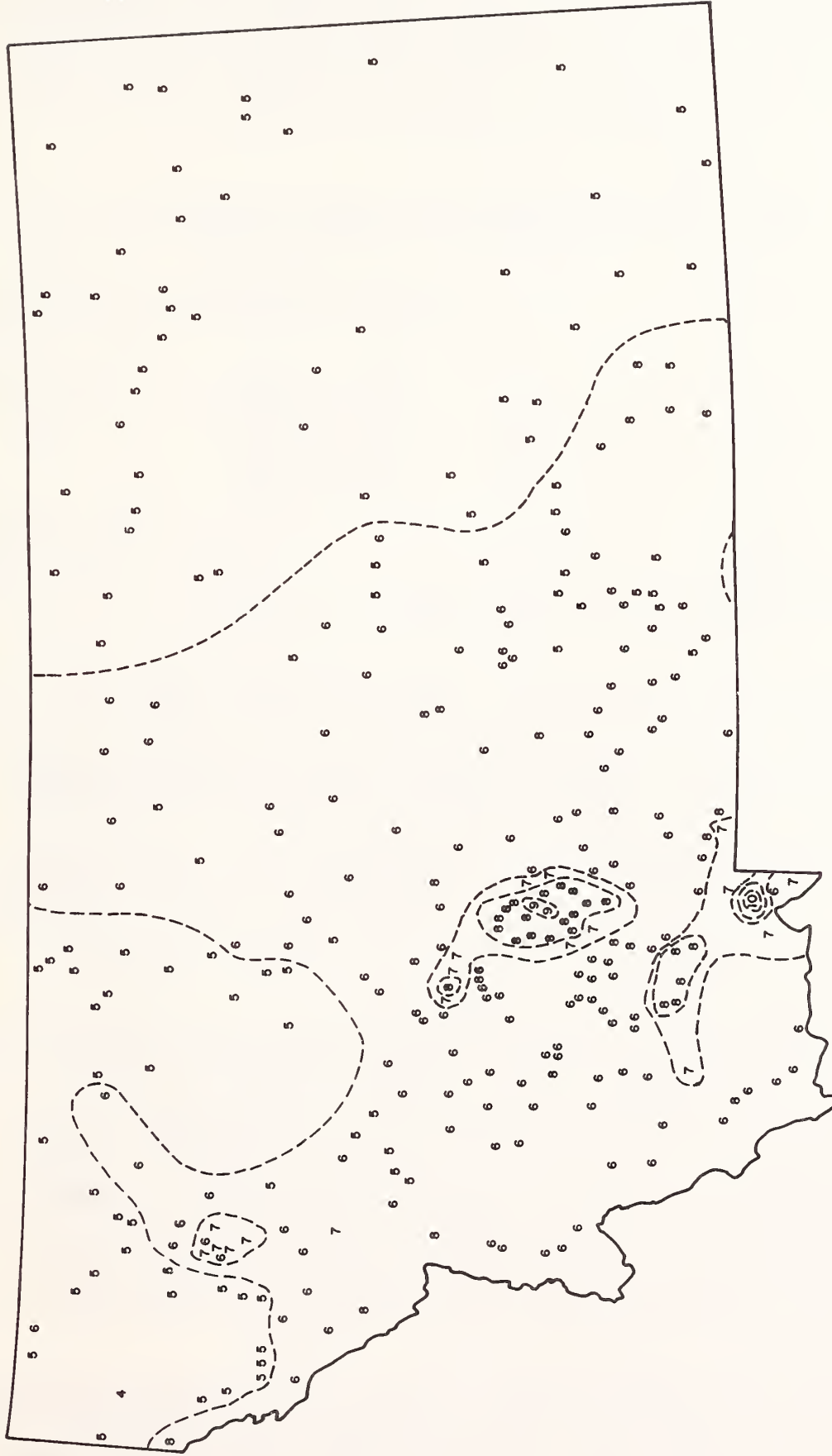
MEASUREMENT

Reported intensities of all major earthquakes in Montana were reexamined using Pardee (1926), annual issues of United States Earthquakes, and the NOAA computer file (USDC 1977a) of intensity data.² The data from all earthquakes were superimposed to produce figure 1, which shows the maximum earthquake intensity (according to the Modified Mercalli Scale) ever reported in Montana. Contours which roughly separate zones of different intensity also are drawn. Because of the variability in reported intensity values, contours are not placed around every single intensity value shown in figure 1; rather, a smoothed version is given.

Whether a map such as figure 1 should be used directly for design purposes is debatable; the issue is whether maximum reported historical intensities should be used for pipeline design. Because figure 1 shows maximum historical intensities and not maximum possible intensities, it probably should be considered to represent the lower range of expected intensities for which to design the pipeline. The justification for this is that generally a design must accommodate an earthquake at least as large as the biggest earthquake recorded in the past. Other factors, such as site geology, should also be considered in design measures. Furthermore, the map includes events that occurred between 1925 and 1977 only. It may therefore underestimate maximum historical intensities in eastern Montana if the 1909 earthquake listed in table 1 is considered.

² The NOAA computer file of Intensity Data was obtained from NOAA in a preliminary form for the Montana area. NOAA calls it the Earthquake Intensity File. It may be obtained from Carl A. von Hake, National Geophysical and Solar-Terrestrial Data Center (D62), Boulder, Colorado 80302.

FIGURE 1. Maximum modified Mercalli intensity experienced in Montana.



SOURCE: (USDC 1977^a) NOAA computer intensity data file, and Pardee 1926; interpreted by University of Montana Earthquake Research Laboratory 1979.

NOTE: All historical quakes, 1925-1977.

^aWhile Roman numerals are generally used to indicate a measure of intensity, intensity here is indicated in Arabic numerals to make the map more readable.

Intensities sometimes are used to estimate ground acceleration at a site. Many authors have found relationships between these quantities (see Bolt 1975 for a summary), but there is a great deal of variation in the findings. The problem is that the earthquake mechanism and local geology can complicate an otherwise predictable relationship between intensity and acceleration. Table 1 gives published ranges of acceleration as a function of intensity.

TABLE 1. Ranges of acceleration as functions of intensity.

Intensity ^a	Published Range of Acceleration (g's)
VI	.005 - .065
VII	.010 - .20
VIII	.025 - .35
IX	.05 - .90
X	.10 - >1.0

SOURCE: After Bolt 1975.

^a According to the Modified Mercalli Scale.

Few recorded accelerations have been taken in Montana, especially close to an epicenter. Accelerograms have been recorded at Hungry Horse Dam in northwestern Montana, Great Falls, Helena, Butte, and Bozeman from the 1935, 1947, and 1959 earthquakes (see appropriate issues of United States Earthquakes and Ulrich 1936). Table 2 summarizes the data. In the table, the column labeled "Vertical" contains acceleration values of ground motion measured by instruments sensitive only to up-and-down motion. The column labeled "Horizontal" contains accelerations measured by instruments sensitive only to sideways, or horizontal motion. In any earthquake there would be complex ground motion including both horizontal and vertical components.

The only recording ever taken of ground acceleration in Montana from a moderately large earthquake at a close epicentral distance (less than 50 km, or 31 mi) was that of the October 31, 1935, Helena earthquake (table 2). The distance from the accelerograph to the focus of this earthquake is not known because the location of the earthquake's focus is not known; no seismographs existed in Montana at that time. The accelerometer which recorded the October 31 earthquake was installed shortly after the shock of October 18, 1935. The distance from the accelerometer to the October 31 shock is an estimate based on studies of S-P time intervals (see glossary) from small aftershocks that came later and were recorded on the accelerometer. Therefore, comparison of the recorded level of ground acceleration from this event to those of standard curves should be made cautiously.

Numerous studies have been completed on the subject of acceleration as opposed to distance as a function of earthquake magnitude; the curves designed by Schnabel and Seed (1973) are commonly used (also Bolt 1975 and Page et al. 1975). The recorded accelerations in table 2 are low in

comparison to most published curves of the western United States. In table 3, the Schnabel and Seed curves give approximate accelerations in relation to epicentral distance and magnitude.

TABLE 2. Accelerations recorded in Montana.

<u>Event</u>	<u>Accelerograph Location</u>	<u>Distance in km to Epicenter</u>	<u>Maximum Acceleration in g^a</u>	
			<u>Vertical</u>	<u>Horizontal</u>
Oct. 31, 1935 Magnitude 6	Helena	5-10	.093	.138
Nov. 23, 1947 Magnitude 6.25	Bozeman	90	.014	.031
	Butte	145	.009	.029
	Helena	191	.003	.005
	Great Falls	287	.002	.007
Aug. 18, 1959 Magnitude 7.1	Bozeman	96	.033	.065
	Butte	176	.027	.050
	Helena	214	.008	.022
	Hungry Horse Dam	457	.002	.002

^a 1 g = 980 cm/s²

TABLE 3. Acceleration in relation to magnitude and distance to epicenter.^a

<u>Distance in km to Fault</u>	<u>Acceleration</u>		
	<u>Magnitude 5</u>	<u>Magnitude 6</u>	<u>Magnitude 7</u>
5	.35g	.50g	.65g
10	.25	.35	.48
20	.12	.22	.35
40	.05	.10	.19
60	.03	.05	.11

SOURCE: Schnabel and Seed 1973.

CONVERSION : 1 km = .622 mi

^a Each value has an expected uncertainty; these values are not given here, but are mostly in the range from $\pm .05$ to $\pm .07g$.

Significantly higher accelerations were recorded during the San Fernando, California, earthquake of 1971, which had a magnitude of 6.6 (Page et al. 1975). It is uncertain whether the relatively low accelerations recorded during the 1935 earthquakes in Helena are characteristic of Montana earthquakes.

Boore et al. (1978) recently published a revised analysis of strong motion data for western North America (see also Page et al. 1972 and Page et al. 1975). They conclude that acceleration on alluvial sites theoretically could be less than acceleration on bedrock sites during strong ground motion because of the lower strength of the alluvial material. However, in studying the San Fernando, California, earthquake of 1971 they found no significant difference in acceleration recorded on alluvial or bedrock sites (distance: 15 to 100 km, or 9 to 62 mi) even though velocity and displacement were significantly greater at alluvial sites. Also, Boore et al. (1978) note that predicted values of maximum ground acceleration close to a fault vary widely in the literature. For example, three different relations predict values ranging from 0.33 g to over 1.0 g at a distance of 5 km (3 mi) from an earthquake with a magnitude of 6.5. They conclude that "... at the present time, it would be difficult to accept estimates less than about 0.8 g, 110 cm/s. and 40 cm, respectively, for the mean values of peak acceleration, velocity, and displacement at rock sites within 5 km (3 mi) of a fault rupture in a magnitude 6.5 earthquake."

PAST EARTHQUAKES

The first reliably reported earthquake in Montana occurred in 1869 in Helena and produced minor damage at an intensity of V. Lewis and Clark might have experienced a Montana earthquake in 1805 (Ulrich 1936, Coffman and von Hake 1973); however, information on earthquakes before 1925 is scanty.

The major earthquakes in Montana during the twentieth century are listed below in table 4. The quake of May 15, 1909, was felt strongly in northeastern Montana. Where it occurred is unknown, but Coffman and von Hake

TABLE 4. Major earthquakes in Montana since 1900.

Date	Location	Felt Area (mi ²)	Maximum Intensity ^a	Magnitude
May 15, 1909		500,000	VII	6.5?
June 27, 1925	Clarkston (Three Forks)	310,000	IX	6.75
Oct. 18, 1935	Helena	230,000	VIII	6.25
Oct. 31, 1935	Helena	140,000	VIII	6
Nov. 23, 1947	Madison Co., SW MT	150,000	VIII	6.25
Aug. 17, 1959	Hebgen Lake	600,000	X	7.1

SOURCE: Coffman and von Hake 1973.

CONVERSIONS: 1 m² = 2.590 km²

^a According to the Modified Mercalli Scale; see appendix I.

(1973) believe it occurred in southern Saskatchewan. Canadian researchers (Stevens et al. 1972, Agarwal 1962), however, cite evidence that the earthquake actually occurred in Montana. Whatever the location, the eastern part of Montana was strongly shaken as were North Dakota, Saskatchewan, and parts of Alberta and Manitoba.

The largest earthquake ever to occur in the Flathead Lake region (figure 2) had a Richter magnitude of 5.0. The three largest earthquakes in the Flathead region, which were roughly equal in size, occurred in 1952 (no magnitude given, intensity VII), 1969 (magnitude 4.3, intensity VII), and 1975 (magnitude 5.0, intensity VI).

From historical data, Algermissen (1969) prepared a risk map for the United States (figure 3) and revised it in 1976 (Algermissen and Perkins 1976; see figure 4).

EARTHQUAKE RECURRENCE RATES

A critical factor in assessing earthquake hazard is determining the probability that an event of a given size or greater will occur within a specified period of time. Because NTPC estimates a life-length of 20 years for the proposed pipeline, that is the time frame used in this report to determine the level of earthquake risk. If a permissible level of risk can be established, the extent of the mitigating design features can be determined. To do this, it is necessary to determine the size of an event for which a design must be made in order to be, for example, 95 percent confident that the event would not occur in the next twenty years. In order to address these issues, analyses were made of earthquake recurrence rates as a function of magnitude for past and recent earthquakes in Montana.

Earthquakes recur more or less according to the equation:

$$\log N_c = a - b M$$

where: M = magnitude of earthquake

N_c = cumulative number of events having a magnitude which equals or exceeds M

and a and b are constants characteristic of the level of activity of a particular region

The constant a depends not only on the activity of a region, but also on the size of the region and the time period over which the equation applies.

Once a and b have been determined, the probabilities of earthquake recurrence at or below a given magnitude may be computed. This equation may be extrapolated to magnitudes somewhat greater than those for which data exist. The extrapolation must be made cautiously, as discussed below. Hence, if the relation is determined from an analysis of earthquake data for a ten-year period which includes events of magnitude up to 5, perhaps these data can be extrapolated to arrive at the average rate of recurrence of earthquakes with magnitudes of 6 or 7.

FIGURE 2. Subareas in western Montana used to determine earthquake recurrence rates.

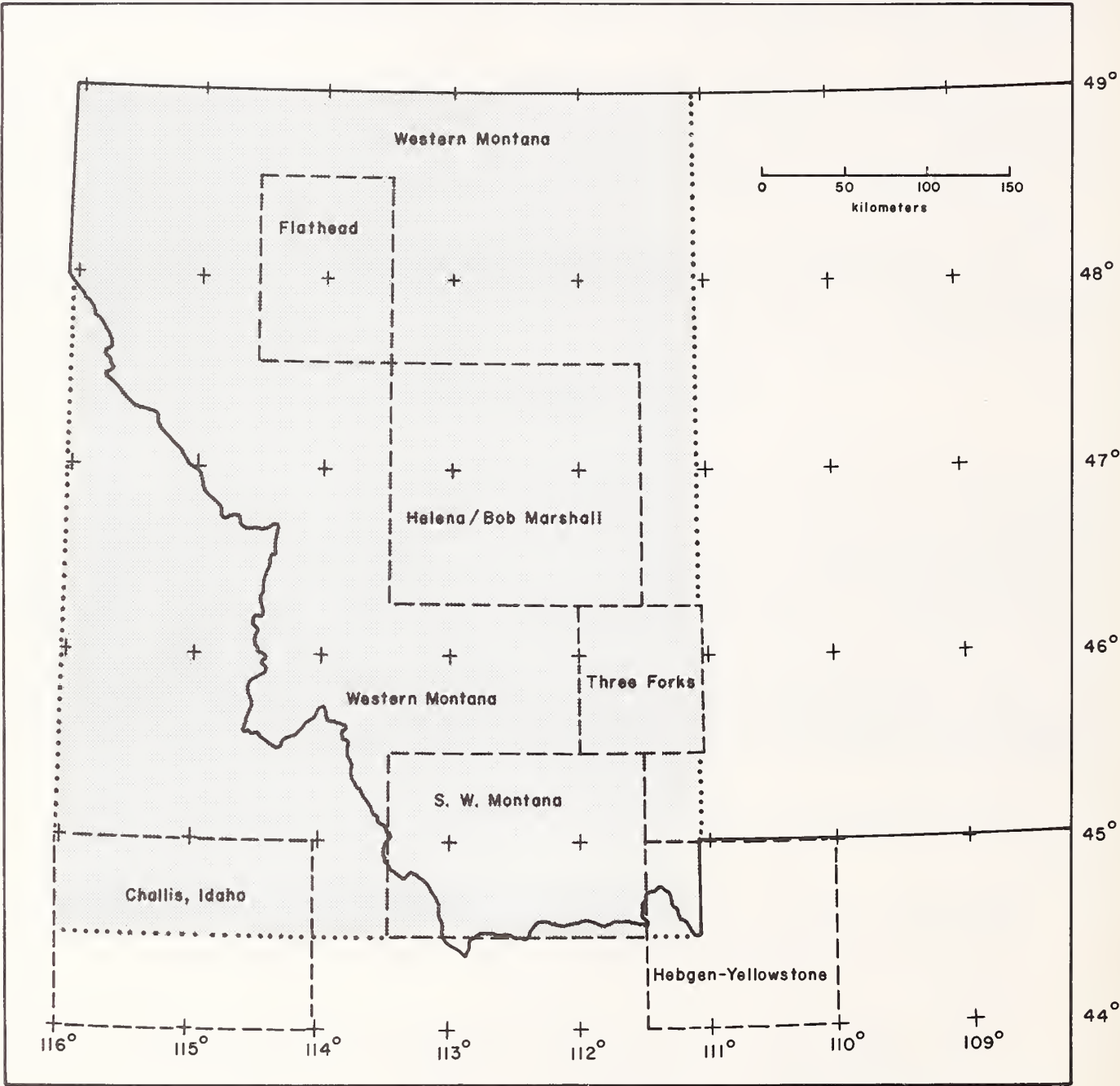


FIGURE 3. Seismic risk map of the United States.



This map is based on the known distribution of damaging earthquakes and the Modified Mercalli intensities associated with these earthquakes; evidence of strain release; and consideration of major geologic structures and provinces believed to be associated with earthquake activity. The probable frequency of occurrence of damaging earthquakes in each zone was not considered in assigning ratings to the various zones.

FIGURE 4. Expected levels of earthquake shaking hazards in the Western United States.^a



SOURCE: Algermissen and Perkins 1976.

^aLevels of ground shaking for different regions are shown by contour lines which express in percentages of the force of gravity the maximum amount of shaking likely to occur at least once in a 50-year period.

An important question arises over the maximum magnitude to which the equation may be extrapolated. For example, it probably is unreasonable to estimate the recurrence rate of a magnitude 9 event for any place on earth. An earthquake of such size has never been reported and may be physically impossible since the size of an earthquake is limited in part by the strength of crustal rock. In certain regions, the maximum credible earthquake may be considerably less; this may be true in the Intermountain Seismic Belt, where earthquakes exceeding magnitude 7.1 have never been reported.

Recurrence rates of earthquakes in western Montana, and in selected subareas (figure 2) within western Montana were calculated. Historical data through 1977 from the NOAA Hypocenter Data File (USDC 1977b) were used to determine the recurrence rates of each region. In addition, a more extensive data set was analyzed from University of Montana seismographs operated during 1974-76. The latter analysis was limited to the Flathead and Helena-Bob Marshall subareas. Critical data resulting from all analyses are in table 5. Figures 5 and 6 show the observed number of earthquakes from the NOAA data file; figure 7 shows recent data from University of Montana records.

The NOAA data are not uniform at all magnitude levels since 1872, the date of the first earthquake studied for this report. The first earthquake with a tabulated magnitude value is the 1925 Clarkston quake. Before 1959, only five earthquakes are of magnitudes listed; all exceed magnitude 6. It is not until 1963 that events with magnitudes of less than 4 are listed. Hence, to determine recurrence rates of earthquakes in Montana, the following assumptions are made:

- 1) Data on quakes of $M \leq 4$ are complete since 1963 (14 years)
- 2) Data on quakes of $4.1 \leq M \leq 5.5$ are complete since 1959 (19 years)
- 3) Data on quakes of $5.6 \leq M \leq 6.5$ are complete since 1925 (53 years)
- 4) Data on quakes of $M \leq 6.5$ are complete since 1900 (78 years)

To determine the average number of earthquakes per year, the numbers obtained from the NOAA data file were multiplied by the factors 1/15, 1/19, 1/53, or 1/78 depending on whether the magnitudes fell under assumption 1, 2, 3, or 4. The cumulative number of quakes per year determined from these adjusted values is shown in figures 8, 9, and 10. These figures also show lines of the form:

$$\log N_C = a - bM$$

It should be noted that they are fitted by eye to the data from each region. In making the fits, care was taken to give low weight to data at low magnitudes, where data are incomplete, and at high magnitudes, where uncertainty in the numbers is greater. Constants a and b , which were thus established for each region, are given in table 6. A constant a' , also given in table 6, normalizes all constants, a , to the value expected for a time period of one year and a regional area of $1,000 \text{ km}^2$ (386 mi^2).

TABLE 5. Search areas for earthquake recurrence rates, western Montana and east-central Idaho.

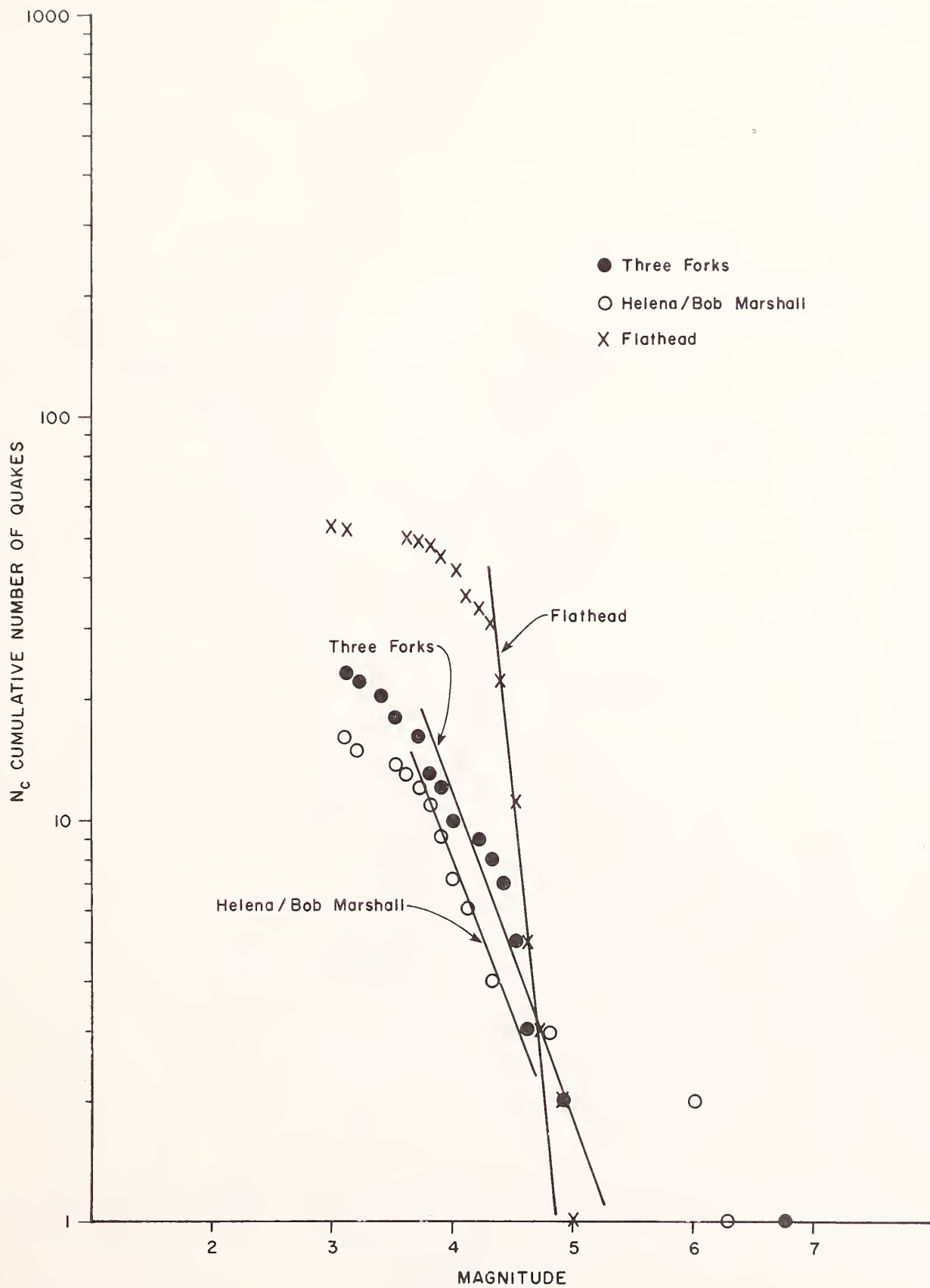
Region	Latitude and Longitude	Approximate Area (km ²)	Quakes with Magnitudes Listed	
			Data Source ^a	Total Number
Helena/Bob Marshall	46.25-47.5 111.5-113.5	21,000	NOAA UM	16 111
Three Forks	45.5-46.25 111-112	6,750	NOAA	23
Flathead	47.5-48.5 113.5-114.5	8,800	NOAA UM	54 167
Southwest Montana	44.5-45.5 111.5-113	17,050	NOAA	44
Hebgen/Yellowstone	44.0-45 110-111.5	13,200	NOAA	137
Challis	44-45 114-116	17,050	NOAA	71
Western Montana (including Idaho)	44.5-49 111-116	102,000 ^b	NOAA	215

CONVERSIONS: 1 mi² = 2.590 km²

^aData sources are the earthquake intensity file (USUC 1977) and the University of Montana.

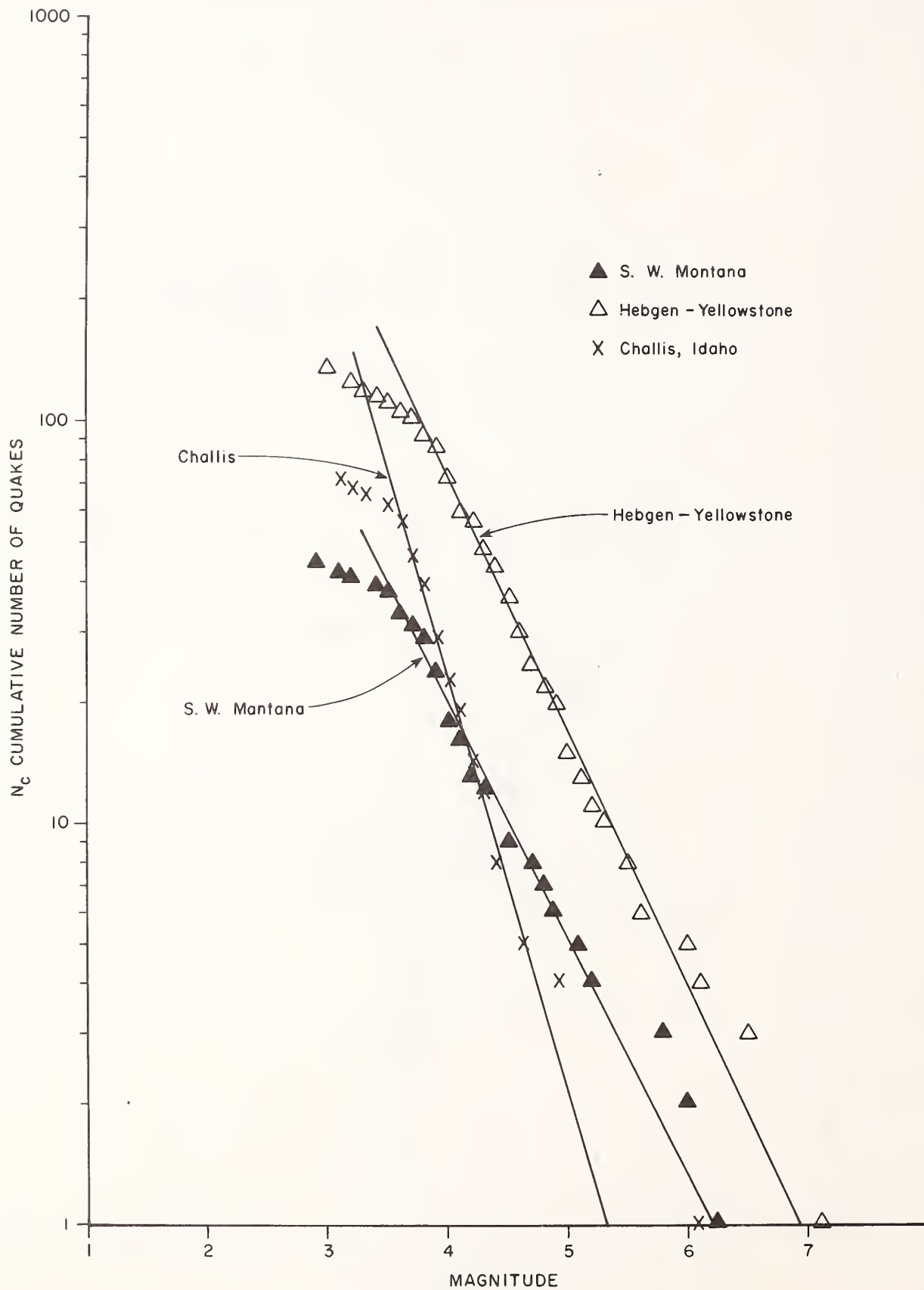
^bIncludes active region only.

FIGURE 5. Earthquake recurrence rate in the Three Forks, Helena-Bob Marshall, and Flathead regions.



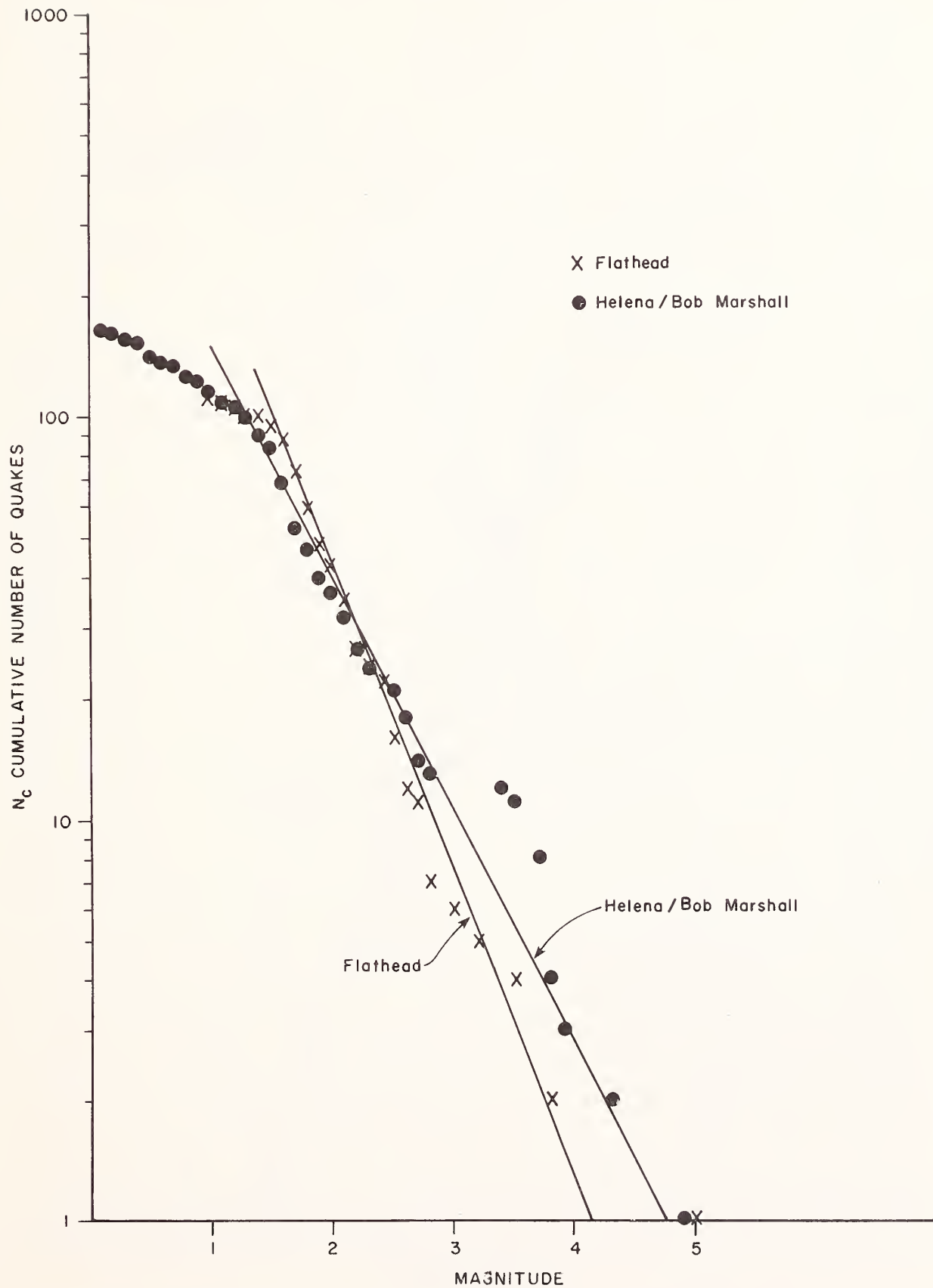
SOURCE: USDC 1977b.

FIGURE 6. Earthquake recurrence rate in the southwestern Montana, Hebgen-Yellowstone, and Challis, Idaho, regions.



SOURCE: USDC 1977b.

FIGURE 7. Earthquake recurrence rates in the Flathead and Helena-Bob Marshall Regions



SOURCE: University of Montana data 1974-1976.

FIGURE 8. Adjusted cumulative earthquake recurrence rates in the Three Forks, Helena-Bob Marshall, and Flathead regions per year.

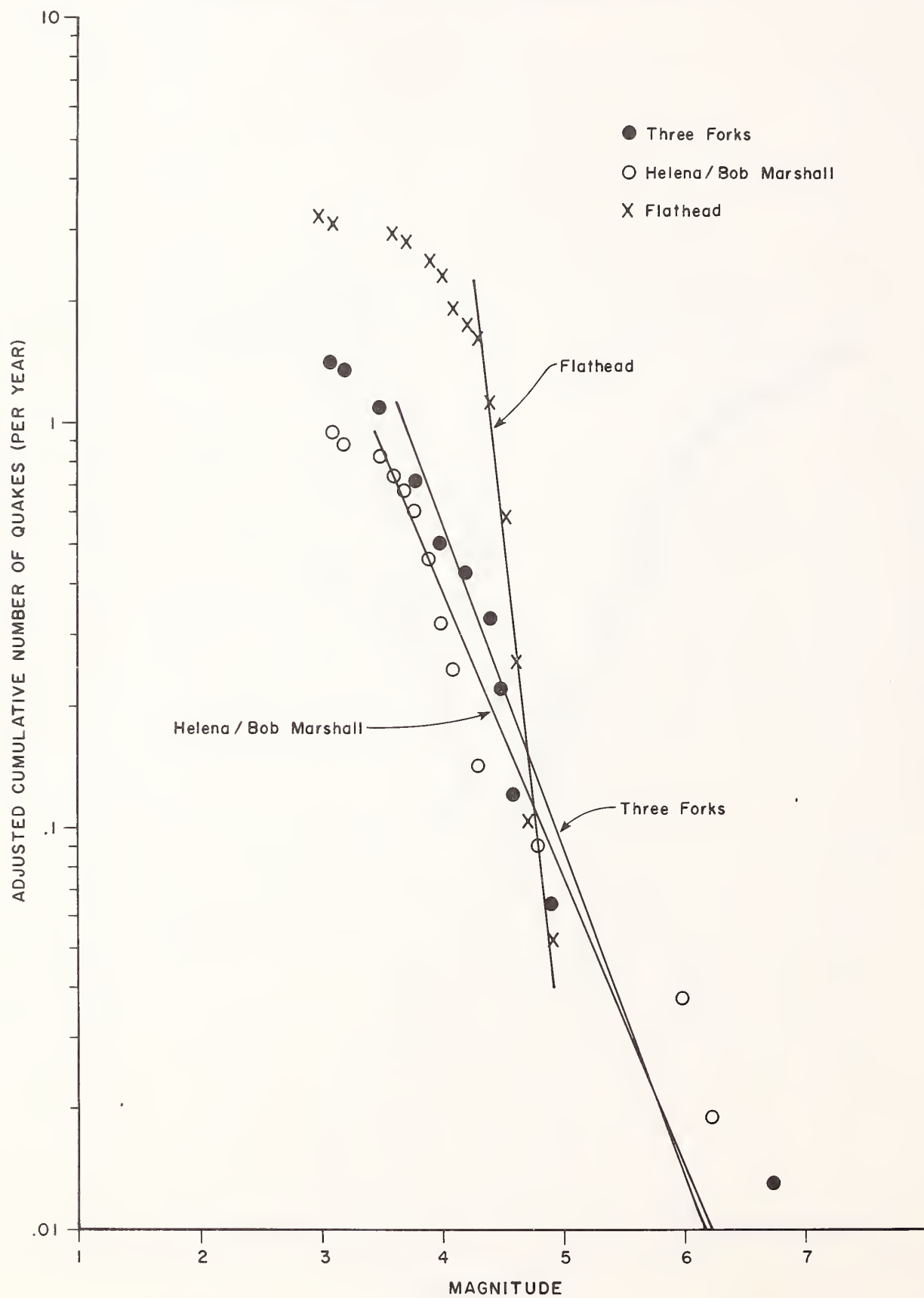


FIGURE 9. Adjusted cumulative earthquake recurrence rates in southwestern Montana, Hebgen-Yellowstone, and Challis, Idaho, regions, per year.

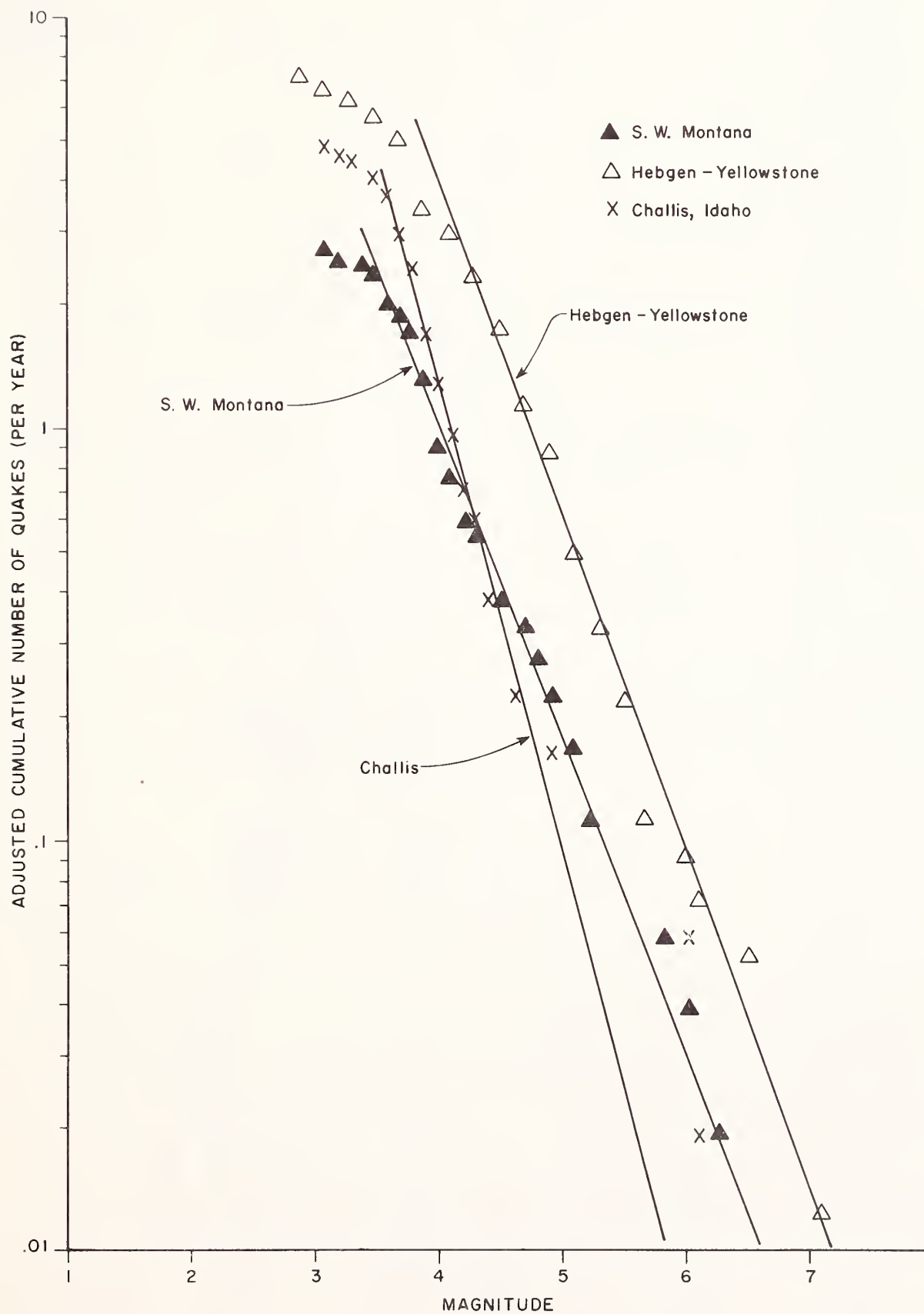


FIGURE 10. Adjusted cumulative earthquake recurrence rates in western Montana, per year.

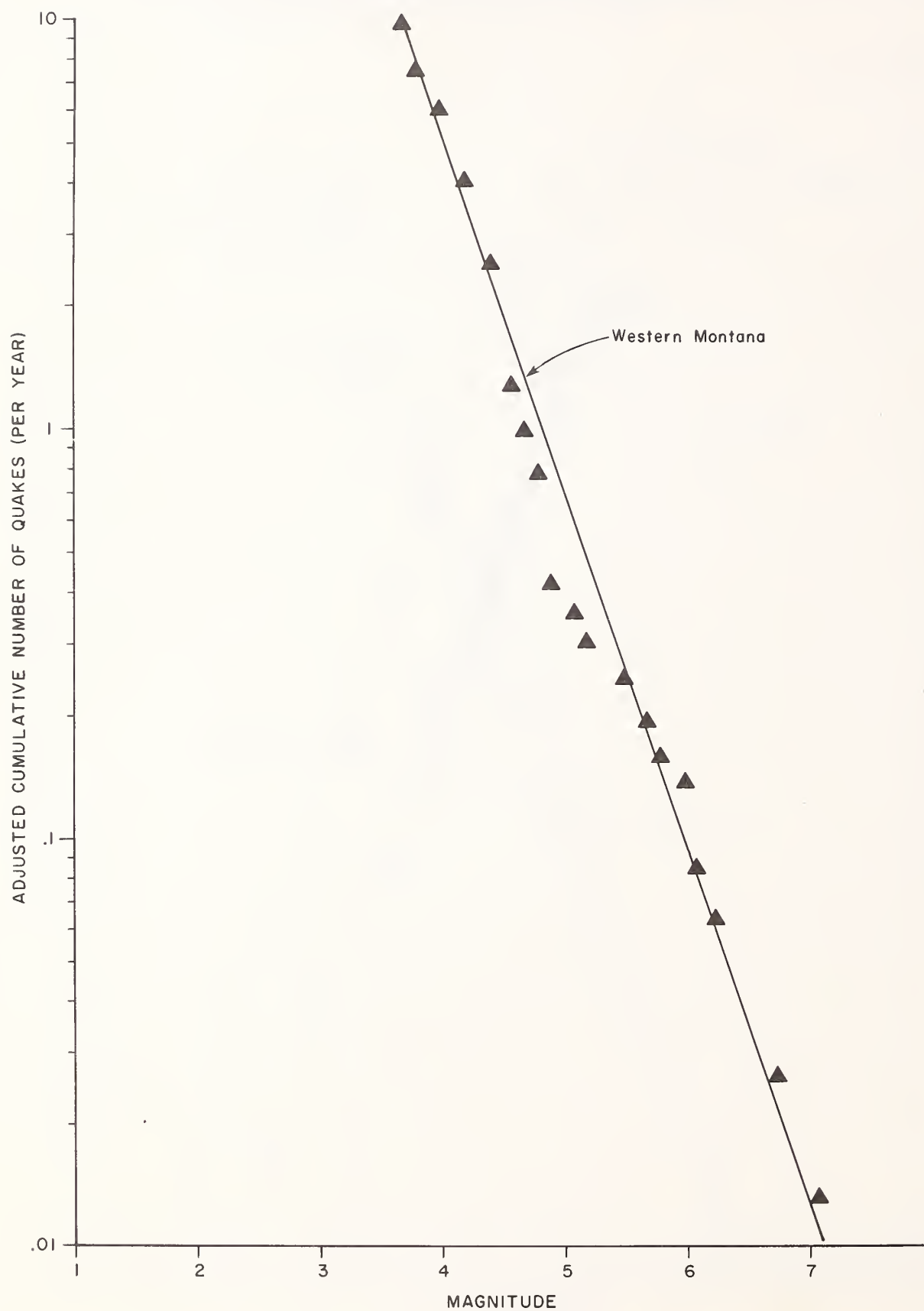


TABLE 6. Earthquake recurrence rates in Montana.

Region	a	b	a'	Recurrence Time (years) in Region			Number of Historical Quakes
				M=5	M=6	M=7	
Helena/Bob Marshall NOAA data	2.45	.72	1.13	14	70	364	2
	2.48	.58	1.13	2.8	11	41	-
UM data (1974-76)							
Three Forks (NOAA)	3.00	.81	2.17	11	73	472	1
Flathead NOAA data	11.4	12.60	10.5	36	14,223	6x10 ⁶	0
	2.98	0.77	1.89	10	57	329	-
UM data (1974-76)							
Southwestern Montana (NOAA)	3.11	.78	1.88	6.0	36	215	2
Hebgen/Yellowstone (NOAA)	3.92	.83	2.60	1.6	11	73	5
Challis (NOAA)	4.77	1.16	3.54	11	162	2,355	2
Western Montana (including Idaho)	4.22	.87	2.21	1.4	10	77	8

NOTE: The table presents results of linear fits to earthquake recurrence of form $\log N_c = a - bM$. Regions are given in table 5. The constants a and b in fits are for a one-year period in the region. The constant a' is calculated from the constant a, given the assumption that the area is 1,000 km²(386 mi²).

SOURCE: USDC 1977b and University of Montana data.

Table 6 also lists the average return time of magnitude 5, 6, and 7 events for different regions. The average return time is:

$$T = 1/n$$

where: n = expected number of quakes of that magnitude in one year

For example, the equation:

$$\log N_c = a - bM$$

(figure 5) indicates that about .0135 events of magnitudes greater than or equal to 6 occur in the Three Forks region each year. Therefore, the average recurrence time for such an event is:

$$T = 1/.0135 = 74 \text{ years}$$

Table 6 reveals the following about earthquakes in Montana:

- 1) In western Montana (including parts of Idaho), a $M \geq 5$ event can be expected every 1.4 years, a $M \geq 6$ event every ten years, and a $M \geq 7$ event every seventy-seven years on the average.
- 2) Historical earthquake data from the Flathead region are anomalous in that the number of moderately large quakes is extremely small relative to the number of small quakes. Earthquake activity is high in this region, but no events exceeding magnitude 5 have ever been recorded. One possible interpretation is that at present the maximum probable earthquake to occur here would be smaller than in the other seismic areas of Montana evaluated in this study. However, if only earthquake data from University of Montana seismic stations is considered for 1974-76, the area has relatively normal recurrence behavior showing, for example, a fifty-seven-year return time for $M \geq 6$ events.
- 3) The highest recurrence rate of large earthquakes in Montana appears in the southwestern part of the state, followed by the Helena/Bob Marshall and Three Forks regions.
- 4) In the Helena/Bob Marshall and Three Forks regions, the return time of magnitude ≥ 6 events is about seventy years, and the return time of magnitude ≥ 7 events is 360-470 years. Historical earthquake data and estimates made from detailed mapping and trenching studies of active faults should be consulted when available. However, it is interesting that recent activity in the Helena/Bob Marshall region (from University of Montana data for 1974-76) indicates a higher rate of activity (table 6). The long-term significance of that activity is uncertain.
- 5) Earthquake activity in the northwestern part of Montana near Thompson Falls and in the eastern part of the state east of White Sulphur Springs is so low that earthquake recurrence rates cannot be assessed using the available historical earthquake reports.

Recent University of Montana data (1974-76) support the conclusion derived from historical data that there is low earthquake activity in the northwestern and eastern part of the state.

The following section considers the risk of earthquake damage to pipelines, and, specifically, how the proposed Northern Tier Pipeline could be designed to withstand earthquake activity.

CHAPTER THREE

RISK OF EARTHQUAKE DAMAGE TO PIPELINES

A certain amount of data is available concerning past damage to pipelines and other facilities due to earthquakes. Present risk of earthquake damage may be easier to assess after an examination of past damage is completed. This is done below.

PAST DAMAGE TO PIPELINES IN THE UNITED STATES AND ABROAD

The last important earthquake in the United States occurred in San Fernando, California, on February 9, 1971; it has been the only significant earthquake to occur in this country since the U.S. Department of Transportation began compiling reports of liquid pipeline accidents in 1969. It is described in the following subsection.

Studies of the United States earthquakes prior to 1969 also have been done. Following the discussion of the San Fernando quake, some of these are considered briefly, along with examples of earthquake damage to pipelines in other countries.

SAN FERNANDO EARTHQUAKE

Although the magnitude of the San Fernando earthquake was only 6.6, it produced surface displacements of up to 2.4 m (7.9 ft) on a thrust fault which had not previously been recognized as active (USDC 1973a, USDI 1971). Most pipeline damage resulting from this earthquake occurred in the San Fernando Valley -- a broad, flat plain bounded on all sides by mountains. Quaternary stream-deposited alluvial fans and terrace deposits cover most of the valley. These deposits rest on broadly folded and faulted Cenozoic and Mesozoic clastic sedimentary rocks up to (4,572 m) 15,000 ft thick.

A total of 241 accelerograms were recorded during the San Fernando earthquake (USDC 1973, Hanks 1975), showing that ground acceleration reached 0.5 to 0.75 g's with high-frequency peaks exceeding 1 g. The highest acceleration (1.25 g horizontal and .72 g vertical) occurred on jointed diorite gneiss at the Pacoima Dam.

The accelerograms were recorded at seventy-eight different sites (USDC 1973, Hanks 1975) by recording stations located from 8 to 369 m (5 to 230 mi) from the epicenter. Some of the seventy-eight sites were underlain by alluvium, and others by bedrock. Ground intensity attained a level as high as X (and possibly XI) on the Modified Mercalli Scale in the alluvium of the valley.

No detailed reports exist on how oil pipeline facilities were affected during the San Fernando earthquake, but it appears that relatively little damage

was sustained by facilities in nearby oil and gas fields (USDI 1971). Pipeline breakage occurred in several fields. Minor spillage was noted and several fields lost electrical power for a few hours. Newhall Refining Company, located 18 km (11 mi) southwest of the epicenter, shut down temporarily due to tank and pipeline damage, but no details are available.

Considerable information exists on the response of water mains, water service lines, and natural gas lines. During the earthquake, 856 breaks occurred in water mains and 556 failures occurred in service lines. Most of the breaks occurred in areas of "shattered" earth and fault offset. Nearly every pipeline crossing of faults showing surface displacement produced pipeline rupture or distortion. The water mains varied from 36 cm (14 in) to 61 cm (24 in) in diameter and in age from one to fifty-five years. Pipe material included both cast iron and steel; both types suffered blowouts (often at points of corrosion) from internal over-pressures induced by the earth motion. Failures at pipe joints were common and occurred even in welded joints. Natural gas mains sustained numerous breaks and much pipe buckling in the same area as the damaged water mains. They were of welded steel construction, with diameters from 31 cm (12 in) to 66 cm (26 in). It should be noted, however, that modern, well-maintained crude-oil pipelines with properly installed corrosion-prevention devices would be far more resistant to damage by earthquakes than would water mains, water service lines, and most natural gas lines. Whether any of the pipelines damaged in the San Fernando earthquake had the advantage of modern pipeline design is unknown.

Some pipeline breaks were caused by landslides induced by the earthquake. A particularly large landslide, the "Juvenile Hall Slide," measured 270 m (300 yards) wide and 1,214 m (1,333 yards) long. It occurred on a slope averaging only 1.5 degrees. Pipeline breaks were commonly found at locations of direct offsets of the ground. Some breaks occurred in areas of no detectable ground fractures. At these locations, subsurface yield or fatigue fractures were observed in the ground.

Damage to pipelines caused by the San Fernando earthquake correlated well with the degree of ground shaking estimated by the Modified Mercalli intensity assigned to each location. The calculated number of breaks per square mile, n , approximately conforms to the relation:

$$n = -67 + 9.0 I$$

where: I is the average intensity in the square mile in question
and is always ≥ 7.44

The regression line defined by the above equation implies no damage at intensities below approximately VII 1/2; however, pipeline breaks have actually occurred at intensity VII. One important conclusion to be drawn from the data available and the equation is that, on the average, damage to pipelines during the San Fernando earthquake was restricted to areas with intensities exceeding VII. The number of pipeline breaks at intensities VII

through XI in areas (cells) of 2 square miles each in the San Fernando Valley was tabulated. The data for all cells having one or more breaks are given in table 7.

TABLE 7. Pipeline breaks in cells having one or more breaks.

Intensity in Cell	Total Breaks in All Cells at Given Intensity	Number of Cells Having Given Intensity	Average Number of Breaks per Cell at Given Intensity
VII	143	12	12
VIII	49	7	7
IX	159	7	23
X	173	5	35
XI	329	4	82

As explained above, most of these breaks probably occurred in old, unwelded, or cast-iron pipelines, which were not built to meet modern design standards of large crude-oil lines. This analysis thus serves only to establish a limit of intensity below which pipelines of any kind would generally not be damaged.

Studies of other earthquakes show similar results about pipeline failure. Some are described below.

OTHER PIPELINES DAMAGED BY EARTHQUAKES

A review of the data available reveals that other earthquakes in the United States have caused pipeline damage. For example, Lawson (1908) reports that the 1906 San Francisco earthquake, which had a magnitude of 8.2, caused water pipelines crossing the San Andreas fault to rupture.

Another earthquake, about which more information is available, was that which occurred in Alaska in 1964. Its magnitude was 8.6. Pipeline failure resulted from ground deformation and failure rather than from fault offset (Eckel 1967). One hundred pipe failures occurred on the Anchorage water system from landslides and ground fractures. Most of the two hundred breaks in the gas distribution system were the result of lateral and vertical ground movement in landslide zones, although some were caused by ground cracks which, after the quake, showed little or no visible displacement. Water mains in Cordova, however, were unaffected by the earthquake even though this city is about the same distance from the epicenter as Anchorage. An explanation may lie in the fact that much of Anchorage is built on outwash sand and gravel overlying the "Bootlegger Cove" clay, while Cordova is built mostly on indurated bedrock. Eckel (1967) noted that pipelines at the Cordova airport, which is built on alluvial deposits, did suffer failures. A 29-km (18-mi) petroleum pipeline 80 km (50 mi) southwest of Anchorage and 177 km (110 mi) from the epicenter was not damaged, and a 150-km (93-mi) natural gas line with a 31-cm (12-in) diameter running southwest from Anchorage had one small break.

Additional information on the effects of earthquakes on pipelines can be gathered from studies completed in other countries. In May 1976 an earthquake of magnitude 6.5 occurred in northeast Italy. The epicentral region was located within a few kilometers of the modern 107-cm (42-in) Transalpine Oil Pipeline (Duetsche Transalpine Oelleitung 1976). Later tests showed that the pipeline did not leak during this moderate earthquake. Some damage did occur to pump stations, although the pumps themselves were not damaged.

For example, the earthquake damaged the electric transmission substation at one pump station, resulting in a power failure that stopped the pump. No antiearthquake measures had been considered in the design of the pump stations; some instrumentation cabinets used for pump station and electrical power control moved during the earthquake. In the epicentral region, some cracks about 10 to 15 cm (approximately 4 to 6 in) wide were detected in the soil above the pipeline at one river crossing.

The 1976 earthquake in Italy illustrates that a modern, buried oil pipeline can resist ground shaking during a moderate earthquake without failing. It shows also, however, that the design of pump stations can be critical to a pipeline's operation during an earthquake. Furthermore, the ground cracks found near the river crossing indicate the possibility of failure at such sites. The proposed Northern Tier Pipeline would have several river crossings in earthquake-prone areas of Montana. The pipe would be in little danger at these crossings, however, if the pipe were buried below flood-scour depth in a trench at each crossing. Aerial crossings, such as by suspension bridge, would be susceptible to damage by earthquakes; if aerial crossings are used, special site studies would be done, and fine-grained tower foundations such as sand and silt would be avoided.

Another study, done during the earthquakes of 1965-67 in Matsushiro, Japan, further substantiates the belief that a modern, buried oil pipeline could withstand moderate earthquake activity. Sakurai and Takahashi (1969) measured the dynamic strains in underground pipelines, placing strain meters on the pipe and in the ground. The authors conclude that the dynamic behavior of the pipe bears little relation to ground acceleration, unlike the behavior of structures above the ground surface. It appears to depend instead upon ground deformation. Also, they observed no difference between ground and pipeline deformation in earthquakes at or below magnitude 5.3. It could be concluded that, in general, damage to a pipeline due to ground deformation would be a problem only when the ground strains are large, such as in the vicinity of faults and landslides.

There is a possibility that water-surge effects ("water-hammer" effects, or auto-oscillation) could break a pipeline. Damage by water-surge has not been observed or inferred in crude-oil pipelines subjected to earthquakes, nor has the possibility of such damage been subjected to theoretical or experimental study. Sakurai and Takahashi (1969), for example, did not consider possible water-surge effects. Some blowouts due to water pressure, corrosion, and earthquake forces occurred in steel water mains during the San Fernando quake (USDC 1973a). A number of air and vacuum valves as well as ball floats were crushed by water pressure surges.

Many active and potentially active faults exist along the proposed Northern Tier Pipeline route. These are defined and described in the following section.

ACTIVE AND POTENTIALLY ACTIVE FAULTS

The term "active fault" has no universally accepted definition in the literature. For example, Sherard et al. (1974), the U.S. Nuclear Regulatory Commission (1975), and Wesson et al. (1975) all provide different definitions. Although the U.S. Nuclear Regulatory Commission considers faults active if evidence of displacement exists within the last 500,000 years of the Quaternary period, many authors (e.g., Bonilla 1970) would consider a fault active if it has moved within the Holocene epoch (since about 10,000 years ago).

Several criteria are used in this report to define an active fault as opposed to a potentially active or an inactive fault. These are:

- 1) Physiographic or other geologic evidence (as from trenching studies) of disturbances in Holocene sedimentary deposits.
- 2) Evidence of historical surface rupture.
- 3) The occurrence of earthquakes. Many active and extremely hazardous faults, however, appear to be relatively aseismic. That is, faults that show evidence of having moved in historic time (within the past hundred years), or of exhibiting fresh, unweathered topographic scarps along their length are not generating earthquakes on a daily or yearly basis. Earthquakes from such faults are not being detected by nearby instruments. Examples include portions of the San Andreas Fault near San Francisco and Palmdale, the Wasatch Fault in Utah, and the Madison Fault in southwest Montana.
- 4) Instrumental evidence of accumulating regional strain.
- 5) Evidence of structural coupling to another active fault nearby.

Potentially active faults are defined in this report as those that displace Pleistocene deposits (from ten thousand years to about two million years ago) but do not displace Holocene deposits.

Hazards to a pipeline from fault motion arise from two possibilities:

- 1) Fault offset, one of the major earthquake hazards to the pipeline itself. It could result in rupture of the pipeline, although this has not been observed.
- 2) Ground shaking, which can extend a considerable distance from the active fault. The distance to which ground accelerations exceeding .1 g may extend generally does not exceed 100 km (62 mi) even for

the largest earthquakes (Bolt 1975, Schnabel and Seed 1973, and table 4). The specific hazards to a pipeline from ground shaking are:

- a) The triggering of ground failure near the pipeline by events such as landslides or slumps in unstable areas such as river crossings and locations of potential ground liquefaction. Generally, however, ground liquefaction does not pose a significant hazard to modern well-designed pipelines. For a discussion, refer to the draft EIS.
- b) The inducing of fluid overpressures in the pipeline. (See discussion on p. 30.
- c) The dynamic response of pump station and power facilities built above ground. This is probably the most important hazard to the pipeline system.

Few detailed studies have been completed to determine fault activity in Montana. The Army Corps of Engineers has been investigating fault activity in the vicinity of the proposed Libby Reregulating Dam. Their detailed investigations included core drilling and trenching of potentially active fault zones.

In this study, information on active and potentially active faults identified by Pardee (1950) and Witkind (1975, 1977) is integrated with past and recent earthquake data. Pardee and Witkind have identified late Cenozoic faults in Montana, principally on physiographic evidence. It should be noted that it is difficult to reliably determine the age of a fault on physiographic evidence alone. In any case, it would be necessary to "calibrate" this technique for a particular region (Wallace 1978).

Focal depths generally range from 5 to 15 km (3 to 9 mi) (Smith and Sbar 1974, Friedline et al. 1976). The principal active and potentially active faults near the alternative routes for the Northern Tier Pipeline are shown on map 5 in the draft EIS; the identifying numbers beside each fault are those of Witkind (1975). All suspected active and potentially active faults in Montana are in the western part of the state; past earthquakes in Montana, however, seem to bear little to no obvious relation to these. One possible explanation is that the location of past earthquakes might have been misjudged. Qamar and Hawley (1979) have shown that several recent earthquakes placed south of Townsend by the U.S. Geological Survey actually occurred up to 20 km (12 mi) to the southeast in the Three Forks area, and perhaps were associated with the Clarkston Valley Fault (Fault #39, described in appendix B). Regional variations in the velocity of crustal and upper mantle seismic waves may account for this. Friedline et al. (1976) note that the data available from seismograms alone can be used to determine the locations of the 1925 Clarkston and 1935 Helena earthquakes only to an accuracy of ± 25 km (± 15.5 mi). However, many recent Montana earthquakes apparently are not associated with known or suspected active faults. Their epicenters are estimated at uncertainties of no more than a couple of kilometers because they were determined from a dense regional network of seismographs operated by the University of Montana between 1974 and 1976.

It is therefore concluded that:

- 1) Many late Cenozoic faults show little movement today. Whether they are temporarily immobilized, like portions of the San Andreas fault, remains in question.
- 2) Many active faults exist that presently are unmapped.¹

Appendix B summarizes the principal known or suspected active faults along the alternative routes proposed for the Northern Tier Pipeline. It describes also whether present-day seismicity is associated with each fault. In the discussion below, active and potentially active faults along the pipeline route are described. The numbers assigned to each fault identify their locations on map 5 in the draft EIS. Maps have been compiled which show all active and potentially active faults in Montana; they are on file with DNRC in Helena.

HOPE FAULT (#123)

The Hope Fault extends southward at least 90 km (56 mi) from Hope, Idaho, into Montana. The Clark Fork flows along the trench formed by the fault. The pipeline would intersect the southern terminus of this fault just east of Thompson Falls, Montana. There is evidence of both horizontal and vertical (southwest side down) displacements of several thousand feet (cumulative since Miocene times). Pardee (1950) suggests that the faulting has occurred along parallel fractures which produced a wide fault zone and that displacement has not occurred since early Pleistocene. Thus, the Hope fault is possibly inactive.

NINEMILE FAULT (#89)

This fault zone extends about 100 km (62 mi) from the Ninemile Valley to a point about 35 km (22 mi) southeast of Missoula. It is at least as young as Pleistocene and perhaps younger, as suggested by faceted spur ridges and disturbed drainages along the northeast side of the Missoula basin (Van der Poel¹ 1978). There is evidence (Pardee 1950) that the fault zone may be several hundred feet wide. Between Grant and O'Keefe creeks northwest of Missoula, an open syncline in the Tertiary sediments shows considerable deformation near the fault where the beds are upturned at angles of 44 to 70 degrees. The fault passes through conspicuous saddles on either side of Rattlesnake Creek near Missoula (one is just north of Mount Jumbo). These saddles show hummocky topography indicative of landslides, the age of which are uncertain. The present-day seismicity along this fault is low.

¹It is assumed that unmapped faults exist which reach the surface of the earth. However, some active faults may not reach the surface; the term "active" for these faults is based on criteria presented in the previous section. It should be noted that Witkind classifies the Prickly Pear Fault (#46) in the Helena Valley as a historically active fault even though no surface rupture is visible in the valley.

An examination of earthquakes that occurred during 1974 and 1976 near Missoula recently was completed. A cluster of earthquakes of magnitude less than 2.0 occurred along the Ninemile Fault, providing convincing evidence of low-level present-day movement. The fault is here classified as active, but further investigation is necessary.

HELMVILLE (#158, #159) AND AVON VALLEY (#51) FAULTS

There is little published work about these faults. The prominent scarp of the Helmville Fault forms the northeast boundary of the Garnet Range west of Nevada Creek. The Avon Valley Fault forms the northeast side of that valley and has produced many abrupt and faceted spur ridges aligned along a remarkably linear, northwest-trending zone. Both historical and recent seismicity indicates that these or related faults are active (Stickney 1978), but, as yet, there is no evidence of recent surface displacements. The swarm of earthquakes southwest of Ovando in April 1978 might have occurred on a northwest extension of the Helmville Fault. The largest of these earthquakes (magnitude 4.9 and maximum intensity of VI on the Modified Mercalli Scale) was widely felt in northwest Montana.

HELENA VALLEY FAULTS (#45, #46)

The Prickly Pear Fault (#46) probably was responsible for two earthquakes that occurred in Helena during 1935 (Scott 1936). Their magnitudes were 6.0 and 6.25. Earthquakes in the Helena area have been reported since 1869, and numerous swarms of earthquakes have occurred there. A total of 2,280 earthquakes took place over a 15-month period in the swarm that began in 1935. Another swarm happened in 1945; the maximum magnitude was 4.5. The Helena region remains active today (Friedline et al. 1976).

Recent USGS mapping by R.G.Schmidt and others (USDI 1977) has tentatively identified the Prickly Pear Fault in bedrock northwest and southeast of Helena, where total vertical displacements are as large as 2,000 m (6,600 ft) (northeastern side down). The age of this displacement is not given by USDI (1977), but the study is not yet complete. Evidence of the fault in the Helena Valley is masked by the alluvial fill, and no detailed geophysical studies (e.g., seismic and gravity) have been made to delineate the fault.

Evidence exists also of a major northwest-trending fault (#50) at the northeast side of the Helena Valley with total cumulative displacement (southwestern side down) exceeding 1,000 m (3,300 ft) (USDI 1975); the displacement is observed in Precambrian rocks. It is possible that the fault displaces Tertiary sediments but this has not been fully substantiated. An eastward dip of Tertiary sediments in the eastern part of the valley suggests that they might have been down-warped along the fault. These faults establish the Helena Valley as a down-warped basin similar to other intermontane basins in western Montana.

Exactly where the largest earthquakes of the 1935 Helena series took place is not known, but analysis shows that aftershocks occurred north of

Helena, within 6 km (3.7 mi) of the city. Data from the University of Montana (Stickney 1978) and Friedline et al. (1976) indicate abundant present-day earthquakes northwest and southeast of Helena. Both the Prickly Pear (#46) and the Scratch Gravel Hills (#45) faults are active, according to criteria given on page 3/ in the previous section, but no surface displacements from recent earthquake activity have been associated with these faults. (In fact, no direct evidence of surface displacement on any Montana fault has been associated with an historical earthquake except the 1959 Hebgen quake.)

The Helena region probably is the most likely in the state to have an earthquake that could damage a large number of buildings. During the 1935 Helena earthquake swarm, more than half of the city's buildings suffered damage (Ulrich 1936). Although there was no evidence of surface faulting, ground cracks occurred within the city and 10 km (6 mi) northeast of Helena. At the latter site, water carrying sand issued from the cracks. Minor evidence was observed of permanent ground deformation (waves in the streets) and of changes in ground water flow within 20 km (12 mi) of Helena.

FAULTS SOUTHEAST OF HELENA

A number of southeast-trending normal faults lie southeast of Helena. Two of these (#152 and #292) probably are of Quaternary age (Witkind 1975). Little published information exists on the others; some of them (#48 and #49) are inferred from geophysical studies.

FAULTS SOUTHEAST OF TOWNSEND VALLEY (#40, #41) AND CLARKSTON VALLEY FAULT (#39)

A northwest-trending zone of normal faults extends from Deep Creek (Fault #41) southward to Sixmile Creek (Fault #40). Total cumulative displacements (down to the west) of up to about 600 m (about 2,000 ft) occur on these faults. The most recent movement occurred after the Miocene period. The Clarkston Valley Fault (#39) also is post-Miocene (Pardee 1926 and 1950) and might have been responsible for the 1925 Clarkston earthquake of magnitude 6.75 because Clarkston Valley was the area of highest intensity as estimated on the Modified Mercalli Scale. The Clarkston Fault, which bounds the valley on the east, apparently is the youngest fault observed. No fresh displacement on the Clarkston Fault occurred at the surface in 1925, although ground cracks occurred at several locations. Microearthquake surveys show that this fault is very active today (Qamar and Hawley 1979). The Helena shock of 1935 and the Clarkston quake of 1925 may be representative of the earthquake potential on all faults in the Helena-Bozeman region. Several arguments support this conclusion. These faults are similar to the many normal faults in the region which border Tertiary intermontane basins in western Montana. Present-day seismicity indicates that these faults and others are presently active. Bold, steep scarps on the north-trending Madison and Tendoy faults in southwestern Montana indicate that large earthquakes on these normal faults occurred in Recent time.

DESIGN OF THE NORTHERN TIER PIPELINE ACCORDING TO LEVEL OF RISK

CALCULATED LEVEL OF RISK

Equation 1, below, uses the Poisson approximation³ to the binomial distribution to approximate the probability distribution of the number of earthquakes of certain magnitude that could occur over a given period of time.

$$\text{Equation 1: } P(x=k) = \frac{(pt)^k}{k!} e^{-pt}$$

where: x = random variable -- number of occurrences
 k = number of earthquakes
 p = probability for an earthquake to occur
 t = project lifetime in years
 e = base of natural logarithms

The return time (number of years before an earthquake recurs) is as follows:

$$\text{Equation 2: } T = 1/p$$

Two useful equations which can be derived from Equation 1 follow. The probability that no events of the given size or more will occur in the next t years is shown by Equation 3.

$$\text{Equation 3: } P(x=0) = e^{-pt}.$$

The probability that one or more events of the given size or more will occur in the next t years is shown by Equation 4.

$$\text{Equation 4: } P(x \geq 1) = 1 - e^{-pt}.$$

³The Poisson model arises from the assumption that earthquakes are randomly distributed in time (an assumption that holds only if a large area -- some tens of kilometers on a side -- is considered). The probability of an earthquake is assumed to be independent from the occurrence of previous earthquakes. This assumption could fail for periods of time during which aftershocks are occurring. The random occurrence of quakes leads naturally to a binomial distribution which, for small values of p , is closely approximated by a Poisson distribution (Cramer 1966).

The Poisson model has not been tested for Montana data, although it has been found to apply by some investigators (Gardner and Knopoff 1974). This section is designed to point out important ideas about return time and level of risk. The conclusions would be virtually the same if the probability distribution were binomial or Gaussian (normal).

Given a certain project lifetime (t) and a certain return time (T), the equations 1 through 4 give the level of risk that the event would occur. For example:

$$\text{if } T = t, \text{ then } P(x \geq 1) = 1 - e^{-T/t} = 1 - e^{-1} = 0.63$$

That is, if the life of the pipeline is twenty years, it would generally not make sense to design the pipeline to withstand an event no larger than the event with a return time of twenty years because the probability of one or more such events with a larger magnitude occurring in a twenty-year period is 0.63. Stated another way, there would be only about a one-in-three chance that the event would not be exceeded. Table 8 shows other risk rates according to return time.

TABLE 8. Risk levels used in pipeline design.

P(x=0) (Probability of not being exceeded)	T/t (Return time during twenty-year life of project)
.37	1.
.50	1.44
.75	3.48
.90	9.49
.95	19.5
.99	99.5

Table 8 indicates that at a .95 probability of not being exceeded during a project lifetime of twenty years, the earthquake magnitude for which the pipeline is designed must have a return time:

$$T = 19.5t = 19.5 \times 20 \text{ years} = 390 \text{ years}$$

This return time corresponds roughly to magnitude 7 in the Helena/Bob Marshall and Three Forks regions. Thus, it would be advisable to design a pipeline in these areas to accommodate an earthquake magnitude of at least 7. If a lower level of risk were desired the pipeline could be designed to accommodate a lower magnitude earthquake, which could be found (approximately) by interpolation from table 8, for any given region.

The historical record of earthquakes in Montana is short--about one hundred years for events of large magnitude. Since the return time for a magnitude-7 earthquake in the combined Helena/Bob Marshall and Three Forks regions is projected to be $(1/364 + 1/472)^{-1} = 206$ years (from table 8),

it would be difficult under any circumstances to obtain a reliable estimate of the actual recurrence rate from historical seismic data. A critical question is whether an earthquake of magnitude 7 could occur in this region. Most earthquake activity in Montana is produced by a stress system which results in a predominance of normal and strike-slip faulting (Smith and Sbar 1974). Faults in the Helena region certainly conform to this pattern. Since earthquakes have occurred in Montana at magnitudes of 6.75 and 7.1, it seems appropriate to assume that an earthquake of magnitude 7 may be possible near Helena.

The following discussion considers the maximum credible earthquake that could occur along the proposed Northern Tier Pipeline route.

MAXIMUM CREDIBLE EARTHQUAKE

There is a rough relationship between the magnitude of an earthquake and the length of the fault rupture which accompanies it (Hoffman 1974, Bolt 1975).⁴ Although the relationship appears to be regionally dependent and has not been established for Montana, it is useful to examine some representative values (table 9) and then estimate its limits on the size of an earthquake. For example, if a fault cannot be mapped continuously for more than 30 km (19 mi), table 9 indicates that the "maximum credible" earthquake on that fault would have a magnitude of 6.5.

TABLE 9. Fault rupture length versus earthquake magnitude.

Rupture Length (km)	Richter Magnitude
5-10	5.5
10-15	6.0
15-30	6.5
30-60	7.0
60-100	7.5
100-200	8.0
200-400	8.5

Conversion: 1 km = .622 mi.

SOURCE: Bolt 1975.

⁴Some seismologists have suggested that fault length is not the critical factor in determining credible magnitude but, rather, the area of the contact surface of the fault itself, below the earth's surface; they suggest that the energy released over this area determines magnitude. However, in Montana, the depth of the fault zone is limited to a few kilometers, perhaps no more than 16, which is the approximate depth of the deepest quakes. Under these circumstances, the area of the contact surface of a fault is proportional to the length for very large earthquakes. Thus, fault length can be used to estimate maximum credible earthquakes, as done in table 9.

The relationship in table 9 would appear to limit the maximum credible earthquake on many of the faults along the proposed Northern Tier Pipeline route to about 6.5. On these grounds, only a few faults have the potential for an earthquake exceeding magnitude 7. These include the Hope, Ninemile, Mission, Swan, and possibly the St. Mary's and Helena Valley faults. Sometimes a question arises over whether a fault zone can be considered continuous or discontinuous, in shorter segments. For example, in mapping the St. Mary's and Helena Valley faults, it is not clear what their continuous lengths are. The St. Mary's Fault has been mapped in two ways--as a continuous feature and as a series of shorter fault segments.

MITIGATING MEASURES

- 1) Since little is known about the active and potentially active faults along the proposed Northern Tier Pipeline route, it would be advisable to complete detailed studies of critical faults before final route selection.
- 2) Special investigation and appropriate design would be especially necessary in the Helena-Lincoln region (including the vicinity of Townsend), in the Nevada Valley, along the Ninemile Fault west of Missoula, and along the Hope Fault east of Thompson Falls.
- 3) On the critical faults, geological and geophysical surveys of selected sites would be advisable. It would be helpful to use such surveys to determine, if possible, the history of movement on each fault during Holocene time. It would be desirable to include trenching in such surveys. Trenching would involve digging long ditches with a backhoe across areas that might be traversed by a young fault. An examination of the sides and bottom of the trench could show the fault, if present, as an offset of rock layers, or as a set of fractures and crushed rock or discolored soil.
- 4) It would be desirable to include the following design measures into the pipeline's above-ground facilities to reduce earthquake damage: structural modifications to buildings, energy-absorbing foundations, and fail-safe shutdown features in the control system.
- 5) Use of the Schnabel and Seed (1973) curves would be helpful when designing the pipeline and pump facilities.
- 6) NTPC has begun a detailed seismic risk evaluation and development of seismic design criteria. It would be desirable to have DNRC review the final work for this evaluation and final design for seismic loadings.

CHAPTER FOUR

SUMMARY

Earthquakes can produce ruptures in an underground pipeline if the line crosses (1) an active fault on which surface displacement occurs or (2) an area of ground failure (such as landslides and slumping) induced by ground shaking. Theoretically, shaking might induce failure from fluid over-pressure, but this has never been observed in large-diameter oil pipelines. The earthquake resistance of above-ground pump stations and power facilities also must be considered so that they may be designed to preclude operational failures during ground shaking.

Western Montana lies in the Intermountain Seismic Belt, a zone in which earthquakes occur. Several earthquakes have exceeded Richter magnitude 6 and one exceeded magnitude 7. A credible earthquake magnitude for which to design the proposed Northern Tier Pipeline would be 6.75 or 7. The design also could appropriately include an earthquake intensity of IX on the Modified Mercalli Scale.

There are few measured data on ground accelerations in Montana at close distance to a fault. It is therefore suggested that the design of the pipe, pump stations, and associated facilities be based upon acceleration curves like those of Schnabel and Seed (1973) implying an acceleration of 0.60-0.65 g.

Estimated earthquake return times in the Three Forks region at magnitudes 6 and 7 are 73 and 472 years. The return times estimated for the Helena/Bob Marshall region at magnitudes 6 and 7 are 70 and 364 years, respectively.

Although an event greater than or equal to magnitude 6 never has occurred northwest of Helena, it cannot be concluded that one is not possible. Given the recurrence time of such events in Montana, there is a fair chance that such an event would not yet have occurred in historical times.

There are many active or potentially active faults along the alternative routes proposed for the Northern Tier Pipeline. These include the Hope, Nine-mile, Helmville, Avon, and Helena Valley faults and several faults southeast of Helena. Several of these are known to have had displacement during the Quaternary; many are seismically active today. Some potentially active faults are spatially associated with seismicity; that is, evidence of earthquakes is observed in a linear zone parallel to and centered on the fault at the surface, or on its underground extension. Some potentially active faults are not spatially associated with seismicity. Furthermore, not all earthquakes occur near presently known faults. Some active faults may as yet be unmapped, and some potentially active faults may be "locked" but hazardous, like some portions of the San Andreas Fault.

APPENDIX A

MODIFIED MERCALLI INTENSITY SCALE OF 1931 (ABRIDGED)

- I. Not felt except by a very few under especially favorable circumstances.
- II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
- III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
- IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
- V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.
- VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
- VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
- VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
- IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

- X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
- XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
- XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

NOTE: For an unabridged version of the Modified Mercalli Intensity scale see Coffman and Stover (1978).

APPENDIX B

PRINCIPAL KNOWN OR SUSPECTED ACTIVE FAULTS IN WESTERN MONTANA ALONG THE PROPOSED NORTHERN TIER PIPELINE ROUTES

Fault numbers after Witkind (1975). Compiled by Nancy Shrader, Department of Geology, University of Montana.

Fault 38--Bridger Creek, Bear Canyon Fault

Type: High-angle normal

Age: Late Cenozoic, possibly some displacement since Pleistocene (Pardee 1950)

Evidence: Scarplike mountain front, dipping Tertiary lake beds, faceted spurs

Seismicity: Probably low (but see Qamar and Hawley 1979)

Fault 39--Clarkston Fault. East edge of Clarkston basin (near Three Forks)

Type: High-angle normal

Age: Cenozoic though possibly responsible for 1925 earthquake (Pardee 1950)

Evidence: Moderately steep slope, dipping Tertiary lake beds

Seismicity: Active (Qamar and Hawley 1979)

Fault 41--East edge of Townsend valley

Type: High-angle normal

Age: Late Cenozoic (Robinson 1959)

Evidence: Worn fault scarp, dipping Tertiary lake beds, faceted spurs

Seismicity: Active (?) (Many "Townsend Valley" quakes mislocated)

Fault 42--En echelon faults on east side of Townsend Valley

Type: High-angle normal

Age: Late Cenozoic (Pardee 1950)

Evidence: Broken Tertiary sediments, fault scarp, faceted spurs

Seismicity: Active (?) (Many "Townsend valley" quakes mislocated)

Fault 45--Scratch Gravel Hills Fault

Type: High-angle normal (Pardee 1950), left-lateral oblique-slip in northern part (Stickney 1978).

Age: Late Pleistocene (Pardee 1950)

Evidence: Regular front of hills, altered drainage pattern, incomplete valley fill

Seismicity: Very active

- Fault 46--Prickly Pear Fault
Type: High-angle normal
Age: Historic (no ground breakage) (Scott 1936)
Evidence: Well-worn scarp, mature dissection of slope, earthquake of 1935.
Seismicity: Active
- Fault 47--Between northern edge of Elkhorn Mountains and Spokane Hills
Type: High-angle normal
Age: Late Cenozoic? (Witkind 1975)
Evidence: Negative gravity anomalies (Davis et al. 1963)
Seismicity: Unknown
- Fault 48--Western flank of graben also defined by Fault 47
Type: High-angle normal
Age: Late Cenozoic? (Witkind 1975)
Evidence: Negative gravity anomalies (Davis et al. 1963)
Seismicity: Active?
- Fault 49--Underlies Canyon Ferry Reservoir
Type: High-angle normal
Age: Late Cenozoic? (Witkind 1975)
Evidence: Negative gravity anomalies (Davis et al. 1963)
Seismicity: Very low?
- Fault 50--St. Mary's Fault (see also fault 94)
Type: Right-lateral oblique-slip
Age: Late Cenozoic (Witkind 1975)
Seismicity: Unknown
- Fault 51--Northeast edge of Avon valley
Type: High angle normal
Age: Late Cenozoic (Witkind 1975)
Evidence: Faceted spur ridges.
Seismicity: Active
- Fault 54--Continental Fault
Type: High-angle normal
Age: Historic and/or Holocene (Pardee 1950)
Evidence: Exposed mine workings, bedrock elevation differences, springs and zones of limonite-stained rocks marking fault trace, precise leveling indicated movement between 1896 and 1906.
Seismicity: Unknown
- Fault 71--East side of Deer Lodge pass
Type: High-angle normal
Age: Late Cenozoic (Pardee 1950)
Evidence: Marked by trenchlike depression, dipping Tertiary lake beds whose relationship with bedrock indicate several parallel fractures
Seismicity: Unknown

Fault 89--Ninemile Fault

Type: High-angle normal in zone several hundred feet wide

Age: Quaternary (Pardee 1950), possibly younger (Van der Poel 1978).

Evidence: Faceted spurs, disturbed drainages

Seismicity: Low, considering cluster of small earthquakes observed along fault during 1974 and 1976, of less than magnitude 2.

Fault 91--Jocko Fault

Type: High-angle normal

Age: Late Quaternary (Pardee 1950)

Evidence: Faceted spurs; bold mountain front dissected by steep, narrow valleys; disturbed lateral moraine

Seismicity: None (?)

Fault 92--Mission Fault

Type: High-angle normal

Age: Late Tertiary or early Quaternary (Pardee 1950)

Evidence: Steep, high-relief mountain front, notched and over-steepened spur ridges.

Seismicity: Low (near southern end?)

Fault 93--Swan Fault

Type: Low-angle normal

Age: Late Cenozoic (Pardee 1950)

Evidence: Steep high-relief mountain front, faceted spur ridges

Seismicity: Low

Fault 94--St. Mary's Fault

Type: High-angle normal and right lateral strike-slip

Age: Late Cenozoic (Pardee 1950), possibly Quaternary

Evidence: Well worn fault scarp along the northeast, gravity anomaly contours and offset of glacial deposits (Kleinkopf and Mudge 1972, Dea 1978).

Seismicity: Active

Fault 123--Hope Fault

Type: High-angle normal

Age: Late Cenozoic (Pardee 1950)

Evidence: Northeast tributaries of the Clark Fork have cut steep valleys in the front slope. Depth of Clark Fork Valley erosion since fault displacement suggests movement not later than early Pleistocene.

Seismicity: None (?)

Fault 126--Mt. Sentinel, Mt. Jumbo

Type: High-angle normal

Age: Late Cenozoic (?) (Pardee 1950)

Evidence: Steep front slope extended by valley deepening, hanging valleys on shallower back slope.

Seismicity: None (?)

Fault 129--Northeast edge of Lincoln Valley
Type: High-angle normal
Age: Late Cenozoic ? (Pardee 1950)
Evidence: Regular mountain front rising from valley
Seismicity: Active?

Fault 152--Extends south from Lake Helena
Type: High-angle normal
Age: Quaternary (Witkind 1975)
Evidence: Quaternary scarp
Seismicity: Unknown

Fault 158--South of Helmville
Type: High-angle normal
Age: Late Cenozoic (Witkind 1975)
Evidence: Bold scarp
Seismicity: Active

Fault 159--Nevada Creek
Type: Left-lateral strike-slip
Age: Late Cenozoic (Witkind 1975)
Seismicity: Active

Fault 292--East of Helena
Type: High-angle normal
Age: Quaternary? (Witkind 1975)
Seismicity: Unknown

Osburn Fault
Type: High angle normal
Age: Late Cenozoic (Pardee 1950)
Evidence: Scarplike mountain front, faceted spurs
Seismicity: None (?)

GLOSSARY

aggregate -- Construction material, such as sand, gravel, or crushed rock, used in concrete, land fill, or manufacturing processes.

alluvium -- Unconsolidated sediment, such as sand, pebbles, clay, or silt, or mixtures of these, deposited by rivers or streams.

amplitude -- The range from the mean value to the largest or smallest value of a wave, such as a seismic wave.

body wave-- A seismic wave that travels through the interior of the earth, and is not related to a boundary surface. Body waves are of two types: longitudinal (P wave) or transverse (S wave).

clastic -- Pertaining to a rock, such as sandstone or shale, or a sediment, such as sand or pebbles, that is derived from pre-existing rock and has been transported from its point of origin.

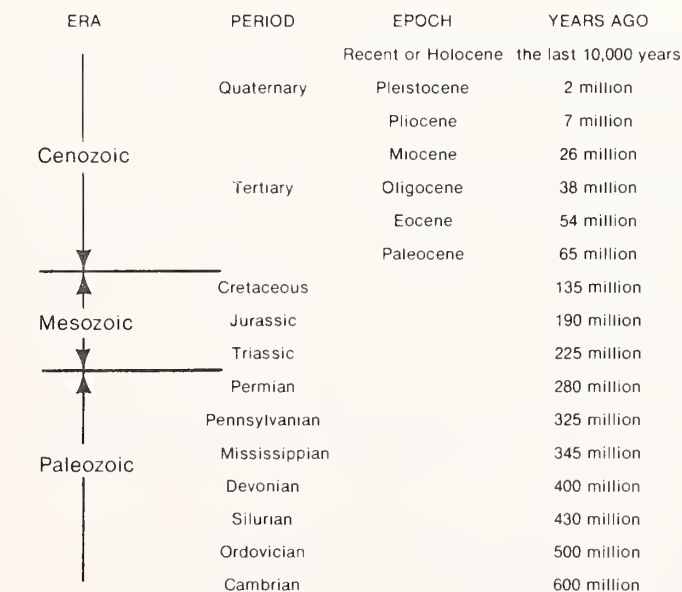
displacement -- The amount of movement produced by a fault as measured in any direction.

epicenter -- The point on the earth's surface that lies directly above the focus of an earthquake.

flocculation -- Aggregation into small clumps.

focus -- See seismic focus.

geologic time -- The period of time beginning with the formative period of the earth as a planet and extending to the beginning of recorded history.



Precambrian -- Precambrian time represents 85% of the earth's history thus far
 NOTE The scale of this figure does not represent the duration of periods, epochs or eras

ground velocity -- Velocity of an earthquake wave that is travelling along the earth's surface.

ground water -- Water in the ground in the zone of saturation. Wells and springs are supplied from ground water.

intensity -- A measure of the effect of earthquakes on humans and human artifacts. See magnitude.

liquefaction -- The temporary transformation of a soil or sediment into a fluid mass, due to shock or strain.

magnitude -- A measure of the strength of an earthquake or the strain energy released by it as determined by seismograph measurements; magnitude measures energy. The Richter scale measures magnitude. Intensity is a measure of the effect the released energy has on humans and human structures, and should not be confused with magnitude.

Poisson distribution -- A frequency distribution dealing with the number of occurrences of an event per unit interval, used where there is a large number of observations and each occurrence is of low probability.

scarp -- A cliff line produced by erosion or faulting.

seismic focus -- The point within the earth that is the center of an earthquake: i.e., the point of origin of an earthquake's elastic waves.

seismic wave -- Wave caused by an earthquake which travels along the earth's surface or through the earth's interior.

shale -- A fine-grained sedimentary rock that splits into flat, thin pieces; formed by the consolidation of clay, silt, or mud.

shear -- A deformation of a substance under stress; adjacent areas are displaced in opposite directions.

S-P time interval -- Difference in arrival time of an S wave and a P wave at a particular place. A larger time interval means the earthquake's focus is farther away.

strain energy -- Potential energy stored in rock by compression; when this energy is released abruptly, an earthquake results.

swarm of earthquakes -- A series of minor earthquakes, none of which is a major shock.

syncline -- A fold in rocks in which the layers dip inward toward a central axis; a cross section of any one layer would reveal a U-shape or some variation of it.

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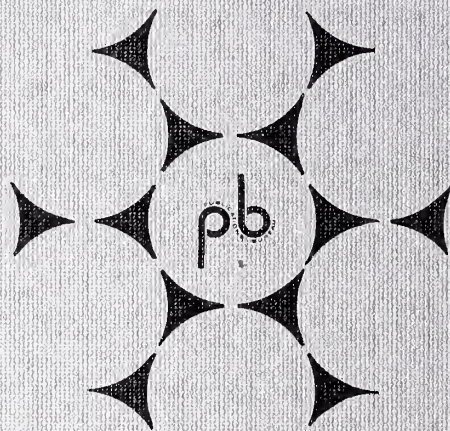
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